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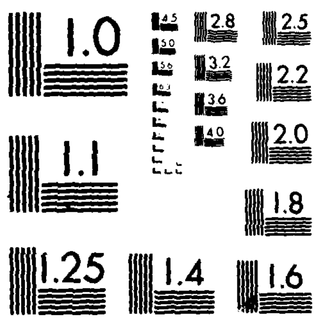

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SEARCH FOR LARGE-SCALE COHERENT STRUCTURES
IN THE NEARLY SELF-PRESERVING REGION OF A
TURBULENT AXISYMMETRIC JET

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In an attempt to explore the existence of large-scale coherent structures in the self-preserving region of an axisymmetric free air jet, a 2.54 cm air jet at a Reynolds number of 46,000 has been investigated for distances in excess of 40 diameters using both long and short time-averaged space-time correlation measurements. Conventional space-time correlation data with probe separations in the streamwise direction by as much as 25 diameters suggest the existence of large-scale coherent structures centered off the jet axis. The radial extent

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) of these structures is about one local jet diameter, and the azimuthal extent is about a quadrant of the cross-section. Time series of short time-averaged correlations between longitudinal velocity fluctuations obtained with two arrays of hot-wires separated in the streamwise direction strongly support the existence of these structures. Nearly periodic peaks and valleys were intermittently observed. A qualitative picture of the spatial characteristics of these structures was inferred from the short time-averaged cross correlation of these time series with a sinusoidal model function. Traces of instantaneous transverse velocity and Reynolds stress as well as the instantaneous velocity vector patterns obtained from a radial array of X-wires also depict existence of large-scale organized motions.

SEARCH FOR LARGE-SCALE COHERENT STRUCTURES IN THE NEARLY SELF-PRESERVING REGION OF A TURBULENT AXISYMMETRIC JET

SUMMARY

In an attempt to explore the existence of large-scale coherent structures in the self-preserving region of an axisymmetric free air jet, a 2.54 cm air jet at a Reynolds number $Re_D = 4.6 \times 10^4$ has been investigated for $x/D \geq 40$ via both long and short time-averaged space-time correlation measurements. Conventional space-time correlation data with probe separations in the streamwise direction by as much as 25 diameters suggest the existence of large-scale coherent structures centered off the jet axis. The radial extent of these structures is about one local jet diameter, and the azimuthal extent is about a quadrant of the cross-section. Time series of short time-averaged correlations between longitudinal velocity fluctuations obtained with two arrays of hot-wires separated in the streamwise direction strongly support the existence of these structures. Nearly periodic peaks and valleys were intermittently observed. A qualitative picture of the spatial characteristics of these structures was inferred from the short time-averaged cross correlation of these time series with a sinusoidal model function. Traces of instantaneous transverse velocity and Reynolds stress as well as the instantaneous velocity vector patterns obtained from a radial array of X-wires also depict existence of large-scale organized motions. It is our plan to continue this research and to obtain quantitative details of these structures and their role in the self-preserving region of the jet.

I. INTRODUCTION

Large-scale coherent vortical motions have been found in so many turbulent flows that there is a fairly widespread belief that these are characteristic features of all turbulent shear flows. While the existence, though not necessarily the precise role, of large-scale coherent structures had been suspected or even known for quite sometime and occasionally investigated (Townsend 1956; Grant 1958; Keffer 1965; Lumley 1965; Mollo-Christensen 1967; Landahl 1967; Kline et al. 1967; Kovasznay et al. 1970; Hussain & Reynolds 1970), the recent upsurge of activity in this topic has been fostered by the discovery of a quasi-deterministic vortex-like structures in flows which otherwise would be regarded as fully (random) turbulent (Crow & Champagne 1971; Brown & Roshko 1974; Winant & Browand 1974; Hussain & Zaman 1975). As a result of this activity, there has evolved a persistent suggestion that these large-scale coherent structures play important roles in turbulent shear flows and perform most of the transports of heat, mass and momentum and production of turbulence energy and noise. Clearly, it is tempting to assume that an "appropriate" superposition of these structures might capture the essential physics of shear flow turbulence and thus, form the basis of a viable theory (Kovasznay 1977; Hussain 1979).

While the presence of these structures in transitional flows and near fields of free shear flows has been well established (Freymuth

1966; Brown & Roshko 1974; Browand & Laufer 1975; Davies & Baxter 1977; Bruun 1977; Yule 1978; Hussain & Zaman 1977) some questions have been raised about the dependence of their nature and role on the Reynolds number and initial or boundary conditions (Chandrsuda et al. 1978; Pui & Gartshore 1978; Hussain & Zedan 1978a,b; Hussain & Husain 1980; Hussain & Clark 1981b). There appear to be sufficient evidences that these structures are also present in equilibrium turbulent boundary layer and wake flows (Kline et al. 1967; Kovasznay et al. 1970; Gupta et al. 1971; Townsend 1979; Falco 1980; Head & Bandyopadhyay 1981). However, the role of the large-scale coherent structures in turbulent shear flows, when present, is still elusive.

In spite of the widespread use of the term, there is neither a well-stated definition of, nor an implicit agreement on, what is precisely meant by a "coherent structure". Even though it is not likely that a simple definition will be agreed upon, it is inescapable that a definition must be put forward as it will be fruitless to discuss an undefined quantity. Hussain (1980) put forward a definition of a coherent structure and emphasized its difference from an eddy as classically defined (Tennekes & Lumley 1974). However, commenting on Hussain's definition, Lumley (1980) points out that spatial superposition is not essential in the definition of an eddy.

For detailed discussion of the coherent structure, analytical considerations in the studies of coherent structures, and experimental constraints in the eduction of the coherent structures, see Hussain (1980). Because of the experimental constraints, coherent structures have been studied in our laboratory in the near fields of plane and circular jets under controlled excitations. These include: response of the axisymmetric jet to controlled sinusoidal excitation (Zaman & Hussain 1980); the coherent structure details during vortex pairing under controlled excitation (Hussain & Zaman 1980); the response of the plane jet near field under acoustic excitation (Hussain & Thompson 1980); the evolution of a "turbulent spot" in an axisymmetric mixing layer (Sokolov et al. 1980; Hussain et al. 1980; Kleis et al. 1981); evolution of a "turbulent spot" in a plane mixing layer (Kleis & Hussain 1980); the mechanism of turbulence suppression in free turbulent shear flows under controlled excitation (Zaman & Hussain 1981a); the preferred-mode coherent structure in the axisymmetric jet (Hussain & Zaman 1981); the applicability of the Taylor hypothesis to the large-scale coherent structures (Zaman & Hussain 1981b); the nature of organization of the axisymmetric mixing layer (Hussain & Clark 1981b), etc. For details of the results, see these publications.

In addition to these studies of coherent structures, some of which are being continued, other studies which have been recently carried out or being performed now include: the phenomenon of self-excitation of a jet with a whistler nozzle, the shear layer tone phenomenon, the phenomena of ring and hole tones, effects of coherent structures and their interactions on jet noise radiation, role of turbulence suppression on jet noise, acoustic-vorticity coupling in unsteady Kutta condition, effects of initial and boundary conditions on the evolutions of free shear flows, coherent structures in boundary layers, Lagrangian statistics and entrainment mechanics in free turbulent flows, interface dynamics through digital image processing, etc.

The relevance of the induced coherent structure, studied by us via controlled excitation — for the convenience of simple phase reference — to the naturally occurring ones is a valid inquiry. Even though claims have been made that the induced structures should be different from the natural ones (for example, Lau 1979), our contention has been that these are not different (Hussain 1980; Hussain & Zaman 1981a). However, it is necessary to demonstrate the validity of our contention through hard data. With this in mind, coherent structures in the near field of unexcited circular jets are being investigated in our laboratory (Hussain & Zaman 1981b). In parallel, we are also investigating the unexcited plane mixing layer and the unexcited plane jet. It should be emphasized that because of the large jitter in the shape, size, orientation, strength and advection velocity of the natural structures, eduction schemes are not likely to be successful in capturing the spatial features of the structures in such detail as has been possible in the excited situations.

As yet, there has been no evidence of the presence of large-scale coherent structures in the self-preserving regions of jets. The broad structural similarities — as revealed by conventional time-average measurements — among wakes, jets, mixing layers, and constant pressure boundary layers (Townsend 1970; Bradshaw et al. 1967), however, would naturally lead to the speculation that the spatial coherence of large eddies should exist in jet flows as well. Measurements of wavenumber-celerity spectrum in the nearly self-preserving regions ($x/D \geq 30$) of plane and circular jets (Hussain & Clark 1981a) also provided an indirect indication of their existence. This study found that the size of most energetic eddies increase in proportion with the local jet width: the streamwise length scale of these eddies is about 3 times the local jet width in the circular jet and 3.5 times the local jet width in the plane jet.

It has been the purpose of the present investigation to conclusively demonstrate existence, as well as document some details of, large-scale coherent structures in the nearly self-preserving region of the axisymmetric free air jet. The approach involved both conventional space-time correlation measurements as well as simultaneous sampling by two linear arrays of hot wires separated in the streamwise direction and eduction of the structure through short time-averaged cross correlation techniques (Townsend 1979; Gupta et al. 1971). It should be emphasized that conventional space-time correlation and short time-averaged cross correlation data can only suggest the presence of large-scale coherent structures; the direct test for the structures must be based on coherent vorticity (Hussain 1980). In order to capture the instantaneous vorticity, Reynolds stress and streamlines, a radial array of X-wires has been employed. Eduction of the coherent structure characteristics from this array will require sophisticated signal processing techniques. These are currently under development.

This report summarizes the progress made during the period September 1, 1979 to August 30, 1980 under the Contract No. F49620-79-C-0227.

II. APPARATUS AND PROCEDURE

The experiments have been carried out in a 2.54 cm axisymmetric air jet at a Reynolds number based on the exit nozzle diameter of 4.6×10^4. The jet facility consists of two settling chambers in tandem designed for controlled excitation study (Zaman & Hussain 1980). The mean velocity and fluctuation intensity profiles at and near the exit of the jet were checked to be axisymmetric. The jet discharges through the center of a 30 cm diameter disc into a large laboratory (15m x 30m x 3.5m) with controlled temperature, humidity, and traffic, so that the flow is essentially free from significant ambient recirculation and disturbances (Bradshaw 1977). The flow facility is schematically shown in Fig. 1, where the dimensions are in cm. The exit centerline fluctuation intensity is 0.25% and is free from any spectral spikes. Further details of the facility and the aerodynamic characteristics of the flow have been documented by Zaman & Hussain (1980).

Longitudinal velocity signals were obtained with seven constant temperature tungsten hot-wires of 4μm diameter operated at a resistance ratio of 1.5 by commercial equipment (both DISA and TSI). The bridge voltages were directly recorded by an eight-channel FM analog tape recorder (HP model 3968A) at a recording speed of 15ips with a frequency response of 5kHz. This frequency response was considered to be adequate for our objective since the frequencies associated with the large-scale structures are considerably lower. The tape recorder has a signal-to-noise ratio of 46dB. The recorded voltages were subsequently digitized through a 12-bit A/D converter, then linearized using the hot-wire response equation and written on a digital magnetic tape (HP 7970E) for numerical analysis by the laboratory minicomputer (HP 2100S). Due to the limitation on the memory capacity available in the minicomputer, each record on the digital magnetic tape was 2.11 s long, with 9.66 ms gap between neighboring records. For long-time correlation measurements, the anemometer voltages were linearized by DISA linearizers (Model 55D10) before analysis by a PAR 101 Correlator. For the longitudinal velocity fluctuations $u_A(t)$ and $u_B(t)$ at spatial locations A and B, the long-time space-time correlation is defined as:

$$R_{AB}(\Delta \underline{x}, \tau) \equiv \lim_{T \to \infty} \frac{1}{T} \int_0^T u_A(t' - \tau) u_B(t') dt' \tag{1}$$

where $\Delta \underline{x}$ is the spatial separation between points A and B, and τ is the time shift between the signals at the two locations.

In order to infer the presence of the coherent structures from the time traces of hot-wire rakes, short time-averaged correlation coefficient $\hat{R}_{ij}$ between longitudinal velocity fluctuations $u_i(t)$ and $u_j(t)$ at the i-th and j-th hot-wire positions was determined through short-time integration defined as follows:

$$\hat{R}_{ij}(t; \Delta \underline{x}, \tau, T) = \frac{1}{T} \int_0^T \frac{u_i(t + t' - \tau) u_j(t + t') dt'}{\hat{u}_i' \, \hat{u}_j'} \tag{2}$$

where $\hat{u}_i'$ and $\hat{u}_j'$ are the short time-averaged rms of u_i and u_j over averaging interval T, i.e.,

$$\hat{u}_i' = \frac{1}{T}[\int_0^T u_i^2(t + t' - \tau)dt']^{\frac{1}{2}} \tag{3a}$$

$$\hat{u}_j' = \frac{1}{T}[\int_0^T u_j^2(t + t')dt']^{\frac{1}{2}} \tag{3b}$$

with

$$u_i = \tilde{u}_i - <\tilde{u}_i>.$$

$\tilde{u}_i$ is the instantaneous longitudinal velocity and $<\tilde{u}_i>$ is its long time-average. Note that the summation convention is not implied for the subscripts i, j in Eq. (3). For each short time-averaged correlation coefficient $\hat{R}_{ij}$, signals were obtained from either the two upstream probes or one upstream and one downstream probes, with i and j denoting the hot-wire locations in the arrays. Since the values of $\Delta\underline{x}$, τ, and T in this study were selected to be fixed, the short-time correlations are simply functions of t alone and are thus denoted as $\hat{R}_{ij}(t)$.

The measurement scheme involved data taken from seven hot-wires, arranged in two configurations. That is, the upstream location at x/D = 40 contained two hot wires separated azimuthally, while the downstream location at x/D = 50 contained a linear array of five hot-wires aligned radially or azimuthally. The arrangements are schematically shown in Fig. 2.

Relative to the conventional long-time average, the short-time averaging process defines a sense of locality in time. To the extent that Taylor's hypothesis is valid (Zaman & Hussain 1981b), the spatial points in the structure corresponding to the points in time can be inferred. If the averaging interval T is chosen to be comparable with the time scale of large eddies, the temporal variations of short time-averaged quantities should be essentially contributed by the large eddies. For neighboring spatial positions in an Eulerian frame, if the velocity patterns of these large eddies passing by the sensors happen to be nearly deterministic, one should expect to observe the same patterns in neighboring time traces of $\hat{R}_{ij}(t)$, for example, reflecting corresponding events. If T is considerably larger than the time scale of large eddies, the identities of individual large eddies will be smeared out.

In order to obtain the radial distributions of instantaneous vorticity and Reynolds stress, a radial array of seven X-wires were deployed at x/D = 50. The radial separation between the adjacent sensors at this station was about 1 in. The voltage outputs from 16-channel in-house built hot-wire anemometers were sampled by a 16-channel A/D converter (12 bit) and stored on a digital magnetic tape. These signals were later retrieved, linearized and decomposed into the longitudinal and radial velocity components (u,v) for each sensor.

III. RESULTS AND DISCUSSIONS

III.1 CONVENTIONAL SPACE-TIME CORRELATION DATA

Before exploring the time traces from arrays of hot-wires, it was considered worthwhile to first infer possible existence of coherent structures through conventional (long-time) space-time correlation data. These data were obtained with two hot-wires separated in the streamwise direction, as schematically shown in Fig. 3. The upstream reference wire was held fixed at the transverse location $y = y_{0.5}$ where the mean velocity is half of the centerline velocity at the same streamwise station. Data were obtained with the second wire traversed either along the same half-width line or over a downstream plane normal to the jet axis. Correlation of the two linearized hot-wire signals was obtained with the correlator.

For each position of the second wire, space-time correlation produced a curve of the typical form shown in the insert in Fig. 4. The peak value of this curve defines the optimum time delay τ_{op}. Fig. 4 shows these long time-average correlations for several data sets obtained with the second wire traversed along the same half-width line. These data have been plotted as a function of time delay τ non-dimensionalized by τ_{op}; the correlation functions are normalized by their peak values. Note that in these non-dimensional coordinates, the correlation functions are essentially the same, independent both of the location of the reference probe and of the spatial separation between the two probes; note further that the separations are sufficiently large.

Fig. 5 shows that the values of τ_{op}, when non-dimensionalized by the local time scales $y_{0.5}/(U_c/2)$ at positions of reference probes, increase linearly with the streamwise probe separation Δx. The contours of constant values of R_{AB} with the upstream probe A located at x/D = 40 and probe B traversed in the axial plane at x/D = 50 are shown in Fig. 6. These values have been uniformly normalized by the rms values at $y = y_{0.5}$ at the two streamwise stations. The correlation is significant within one quadrant and extends radially for about one local jet diameter.

Due to the spatial filtering effect of large separations, the space-time correlations measured should be dominated by the contributions of large eddies. The observed similarity of correlation curves and the linear growth of optimum time delay with streamwise spatial separation were thus considered to be strong indications of existence of orderly large-scale structures.

Based on the long time-average correlation data R_{AB} in Figs. 4 — 6, it appears that the self-preserving region of the axisymmetric jet does consist of large-scale structures which increase in size in proportion to the downstream distance. Its radial extent at any x is about one local jet diameter. An estimate of the longitudinal size of the structure can be obtained from Fig. 4. By extending the R_{AB} data to smaller values at both ends, it is clear that the length of the structure in time is about $3\tau_{op}$. This corresponds to about $6_{y0.5}$ or 3 local jet diameters. Since space-time correlation is dominated by the energetic large-scale structures, one would assume that a direct measurement of the streamwise size of the dominant eddies should produce the same result. Indeed, the most dominant structure as revealed in the wavenumber-celerity spectrum data in the self-preserving region of a 2.54 cm circular jet has been found to have a longitudinal size of 3 local jet diameters (Hussain & Clark 1981a). It is quite interesting that these two essentially independent measurment techniques (namely, the present study and the one reported by Hussain & Clark) have produced identical results.

A caution is in order regarding interpretations of statistical measures. The result should not be regarded as giving the actual sizes of the large-scale structures, nor as suggesting that the structures remain unchanged between the two probes. In fact, it would appear that the large-scale structures will not only experience significant evolutionary changes in shape, size, orientation, strength and convection velocity, but also undergo nonlinear interactions like pairing and tearing as well as slippage (Hussain & Clark 1981b). Furthermore, consistent with observations in boundary layers and wakes (Townsend 1979), it would seem reasonable to expect that the structures will undergo cyclical evolutions of growth, decay and regeneration. The long time-average statistical data in the present study as well as that of Hussain & Clark (1981a) cannot reveal specific details of the structures. Exploration through instantaneous signals from hot-wire arrays, discussed next, was undertaken in order to uncover these details.

III.2 TIME-DOMAIN STUDY OF SIGNALS FROM SINGLE-WIRE ARRAYS

Figure 7a shows a sample of time traces of longitudinal velocity fluctuations from the hot-wires in the radial configuration (See Fig. 2a). Fig. 7b shows the corresponding time traces for the azimuthal configuration schematically drawn in Fig. 2b. Note that some coincidences of velocity undulations are apparent among the traces. However, in order to uncover the possible existence of coherent structures, short time-averaged correlations of these traces are presented in Figs. 8a,b, corresponding to the radial and azimuthal data in Figs. 7a, b. The top trace is the cross correlation of signals from the two upstream probes. The remainder are short time-averaged correlations of signals from one upstream probe and one downstream probe. The top trace has been time-shifted by τ_{op} in order to provide a common reference. It should be clear that there are intervals when the $\hat{R}_{ij}$ traces, especially from adjacent probes, show patterns which are quite similar, indicating passage over the hot-wire array of large-scale coherent structures. Note that groups of quasi-periodic peaks or valleys do intermittently occur in neighboring traces with identifiable phase relationship to one another.

The wake effects of the upstream probes seemed to be insignificant. The mean velocities and the rms of longitudinal velocity fluctuations at the downstream probe positions were checked to be within the measurement uncertainty, with or without the upstream probes in place. The averaging interval T for the short time-averages was selected to be 120 ms which is about two and a half times the local time scale $[y_{0.5}/(\frac{1}{2}U_c)]$ of the mean flow at x = 50D. The time delays for the short time-averaged space-time correlations $\hat{R}_{1j}(t)$, j = 3,...,7, were set to be equal to τ_{op} ($\approx$ 80 msec), the conventional optimum time delay between x = 40D and x = 50D obtained in Fig. 4. The calculated results, as those shown in Fig. 8 indicate that, at least for the purpose of detecting the existence of spatial coherence of large eddies, the choices are acceptable.

The observed orderly patterns and phase coincidences in neighboring traces apparently support the existence of spatial coherence of large eddies passing by the hot-wire arrays. The deterioration of regularities found in the two outer traces $\hat{R}_{13}(t)$ and $\hat{R}_{17}(t)$ in Fig. 8 is consistent with the off-centered spatial extent of the structures, as also suggested by conventional correlation. The close resemblance between the trace patterns of the short time-averaged cross correlation coefficient $\hat{R}_{1j}(t)$ for j = 3,...,7, in addition, provides some measure of evolutionary changes in the large-scale coherent structures between the two stations 10 diameters apart.

The $\hat{R}_{ij}(t)$ traces in Figs. 8a, b were further correlated with a sine wave, and the resulting correlation curve $\hat{C}_{ij}(t)$ are shown in Figs. 9a, b. The quantities $\hat{C}_{ij}(t)$ are defined as,

$$\hat{C}_{ij}(t) = \frac{1}{T} \int_0^T \frac{\hat{R}_{ij}\,(t + t')\; e(t')dt'}{e'^2} \tag{4}$$

where $e(t) = \sin \frac{2\pi t}{T}$, and e' the short time-averaged rms values of $e(t)$. The averaging interval T is equal to the period of the sine wave which in turn is the average period of the nearly periodic peaks and valleys apparent in the traces in Figs. 8a,b. Note that by this short-time cross correlation with the sine wave, the intermittent "periodicity" of trace patterns with "periods" in the neighborhood of that of the reference sine wave was emphasized, and, at the same time, the general phase coincidence and similarities between neighboring $\hat{R}_{ij}(t)$ traces were preserved. Furthermore, this has resulted in smoothing of the signals. Careful examination will reveal close resemblance between traces in Figs. 8 and 9 even though the latter are smoother.

In order to depict more clearly the occurrences of organized patterns, longer traces of $\hat{C}_{ij}(t)$ have been presented in Figs. 10a, b for the radial and azimuthal arrangements of the hot-wires. Each of these two cases contains sufficiently long traces so that each is divided into two parts: (i) and (ii); the traces in (ii) directly follow those in (i). It is clear from these traces that presence of large-scale coherent structures of differing sizes and strengths is identifiable. The intervals when large-scale structures extending over sufficiently long streamwise lengths are present, have been identified. In addition, there are intervals when, even though the duration of phase coincidence does not appear to be long, a characteristic "front" is apparent in most traces. These instants of common characteristic fronts are marked by downward pointing arrows.

III.3 INSTANTANEOUS VELOCITY VECTOR PATTERNS

The presence of a large-scale structure in the turbulent shear flow should produce long-time as well as short-time correlation patterns discussed above. On the other hand, correlation of linear momentum is not a reliable indicator of the presence of coherent structures, whose identification must be based on coherent vorticity (Hussain 1980). With this in mind, the signals from seven X-wires in a radial array were recorded. Fig. 11a shows a segment of the instantaneous velocity vector pattern in a radial plane. As suggested by the solid lines, the large-scale circulation patterns are apparent. There is also a suggestion that the circulation patterns occur in a nearly periodic manner. Similar patterns in consecutive records provide strong support for the large-scale coherent structures.

Fig. 11b shows the time traces of the longitudinal and lateral velocities u(t), v(t) and the Reynolds stress uv(t) at the half-width point. Note the large undulations in both u and v with some phase shift. The large peaks in uv(t) also suggest the dominant role likely to be played by the spatially coherent structures in momentum transfer.

IV. CONCLUDING REMARKS

The purpose of this study was to search for the existence of large-scale coherent structures in the self-preserving region of an axisymmetric free air jet. Conventional long time-averaged space-time correlations between hot-wires separated in the streamwise direction suggest the existence of such large-scale structures. These structures are located off the jet centerline and are as large as the local jet diameter. The azimuthal extent of these structures is about 90°. The streamwise extent of these structures is about 3 times the local jet diameter.

Direct evidence for the occurrences of these structures has been obtained from short time-averaged space-time correlation traces of the longitudinal velocity. These traces have been further smoothed by correlating them with a sine wave of a period typical of the intermittently occurring, nearly periodic peaks and valleys in these velocity traces. The approach, in effect, emphasizes regularities of the trace patterns which are almost periodic with about the same period as that of the reference sine wave, while retaining the general phase coincidences and pattern similarities.

Further direct evidence of the large-scale structure has been obtained from the instantaneous velocity pattern in a radial plane. The velocity vector map in this plane shows well-organized large-scale circulation patterns which occur in a quasi-periodic manner. The time traces of uv(t) also show large coherent Reynolds stresses associated with these structures.

Even though the evidence for the existence of large-scale coherent structures is quite convincing, it is to be remembered that a number of questions regarding the nature of the structures remain unanswered. Since high-speed flow visualization movies of turbulent shear flows reveal rapid evolutionary characteristics and interactions of large-scale coherent structures, it is probably not realistic that the same structures survive longer than a few diameters. In a high Reynolds number mixing layer, we found that the survival distance of a structure is about one structure length (Hussain & Clark 1981b). If a structure survives for a comparable length or longer in the self-preserving region of the axisymmetric jet, there are probably mechanisms for structure renewal. That is, the structure might undergo a cyclical process of growth, breakdown and regeneration (Townsend 1979). Of course, still to be determined are the details of the evolutionary characteristics, the physical description of an average or the dominant structure, and the significance of these structures in transport and Reynolds stress production. We hope to address these questions through further investigations.

The highly creative and productive career of Professor L. S. G. Kovasznay came to a halt on April 17, 1980 by his sudden death due to heart complications. The subject matter of this paper was of utmost interest to him prior to his death. We are seeking funding to continue this research so that the completed work can serve as a proper tribute to his memory.

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FIGURE CAPTIONS

Fig 1. 2.54 cm axisymmetric air jet. The dimensions are in cm.

Fig 2. Schemes of hot-wire arrays.

Fig 3. Scheme for conventional correlation measurements.

Fig 4. Conventional space-time correlations. x_R and x_M, streamwise stations of reference and moving prcbes.

Fig 5. Optimum time delay as function of streamwise spatial separation. U_c local center line velocity at reference probe location.

Fig 6. Distribution of maximum space-time correlation over the transverse plane zt x = 50D. The upstream reference probe is at x = 40D, $y = y_{0.5}$ denoted by o .

Fig 7. Time traces of $u_i(t)$ for Scheme I in (a) and Scheme II in (b).

Fig 8. Time traces of $\hat{R}_{ij}(t)$: (a), corresponding to figure 7a; (b) corresponding to figure 7b. The top trace is time shifted to the right by τ_{op} ($\simeq$ 80 ms).

Fig 9. Time traces of $\hat{C}_{ij}(t)$: (a) corresponding to figure 8a; (b) corresponding to figure 8b.

Fig 10. a. Time traces of $\hat{C}_{ij}(t)$ for Scheme I.

Fig 10. b. Time traces of $\hat{C}_{ij}(t)$ for Scheme II.

Fig 11. a. Vector field of $(\hat{u}, \hat{v})$.

Fig 11. b. Time traces of $\hat{u}(t)$, $\hat{v}(t)$, and $\hat{uv}(t)$ at $y/y_{0.5} = 1$; (arbitrary vertical scales).

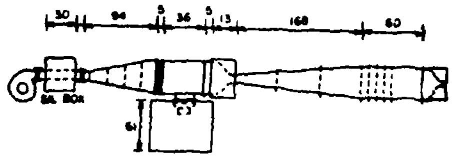


Fig 1.

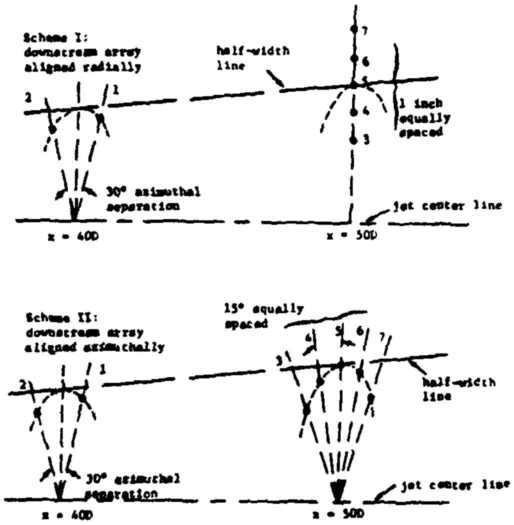


Fig 2.

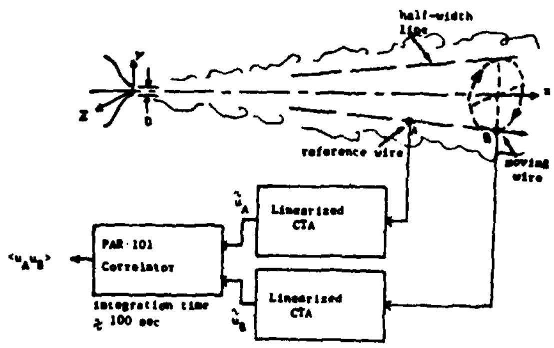
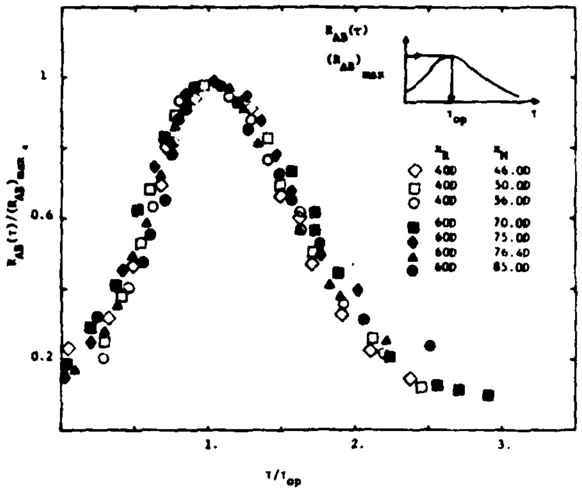


Fig 3.



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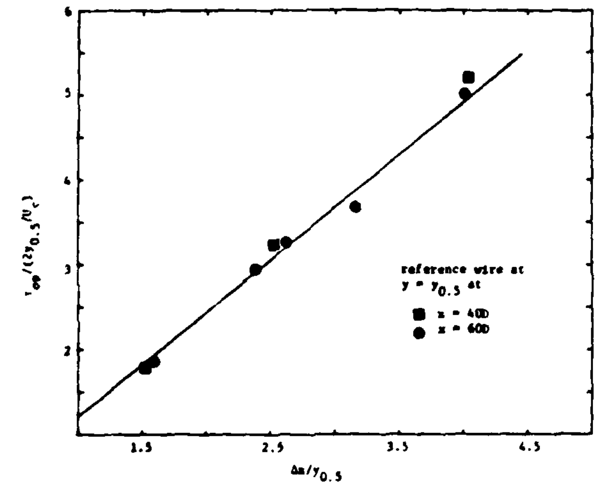

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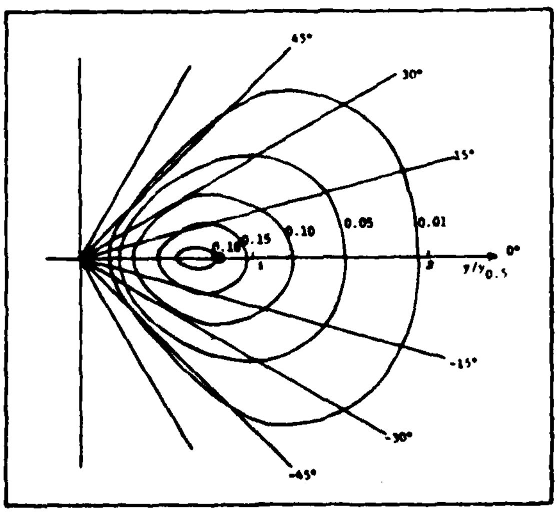

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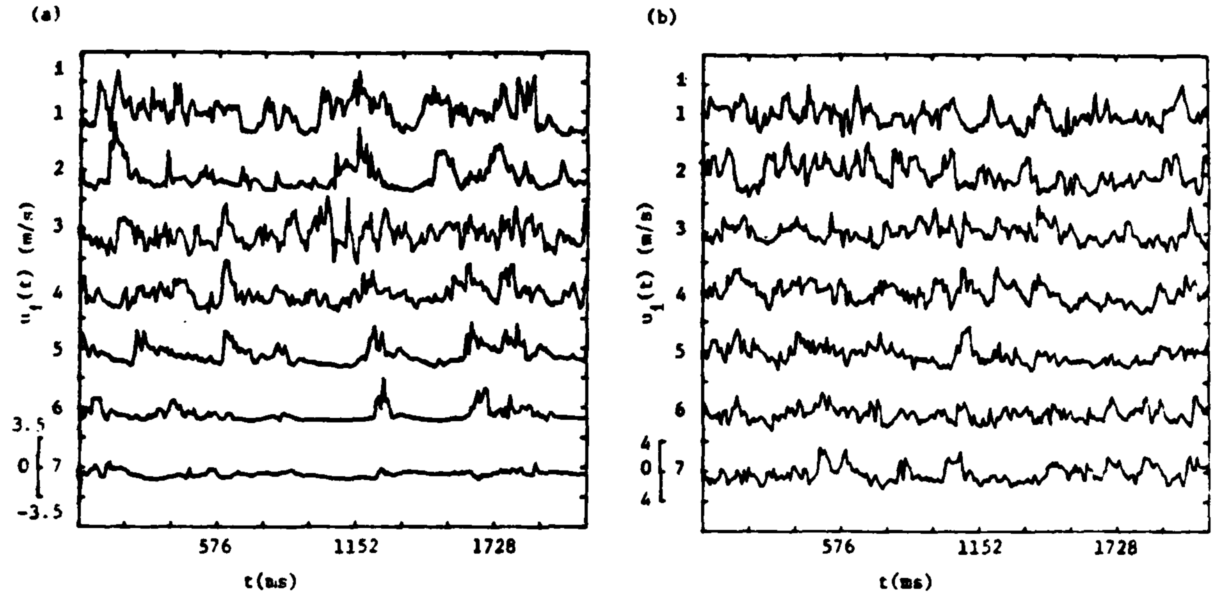

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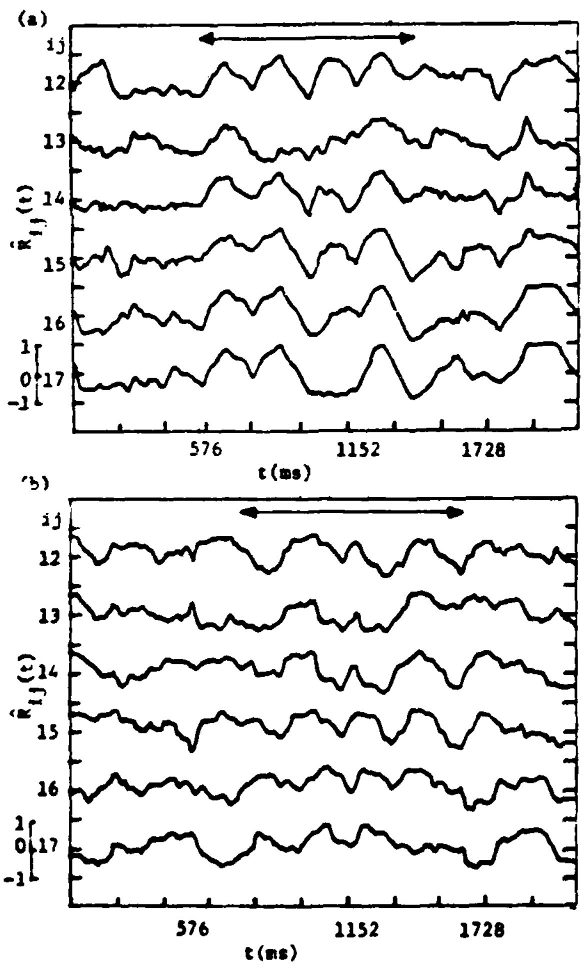


Fig 8.

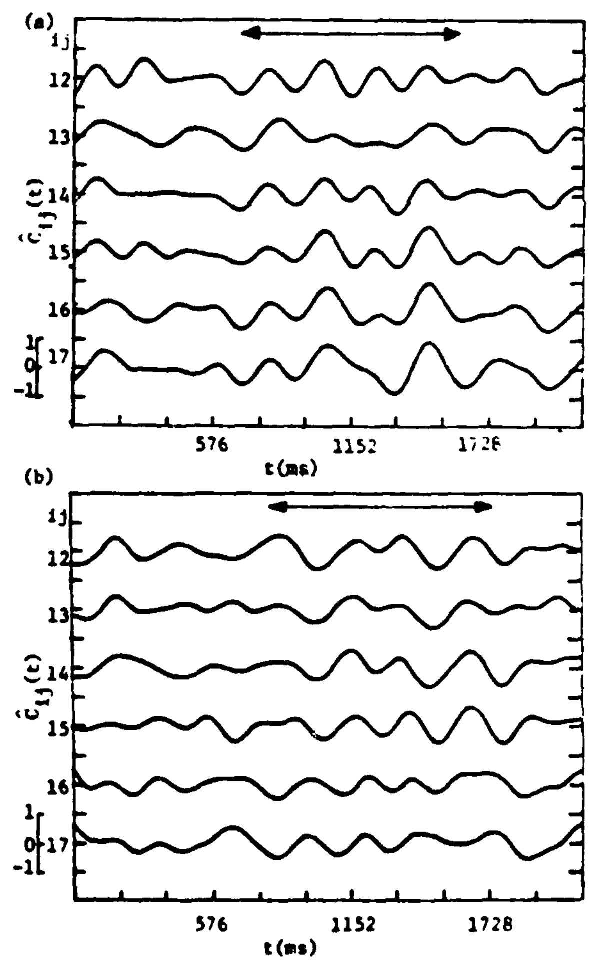
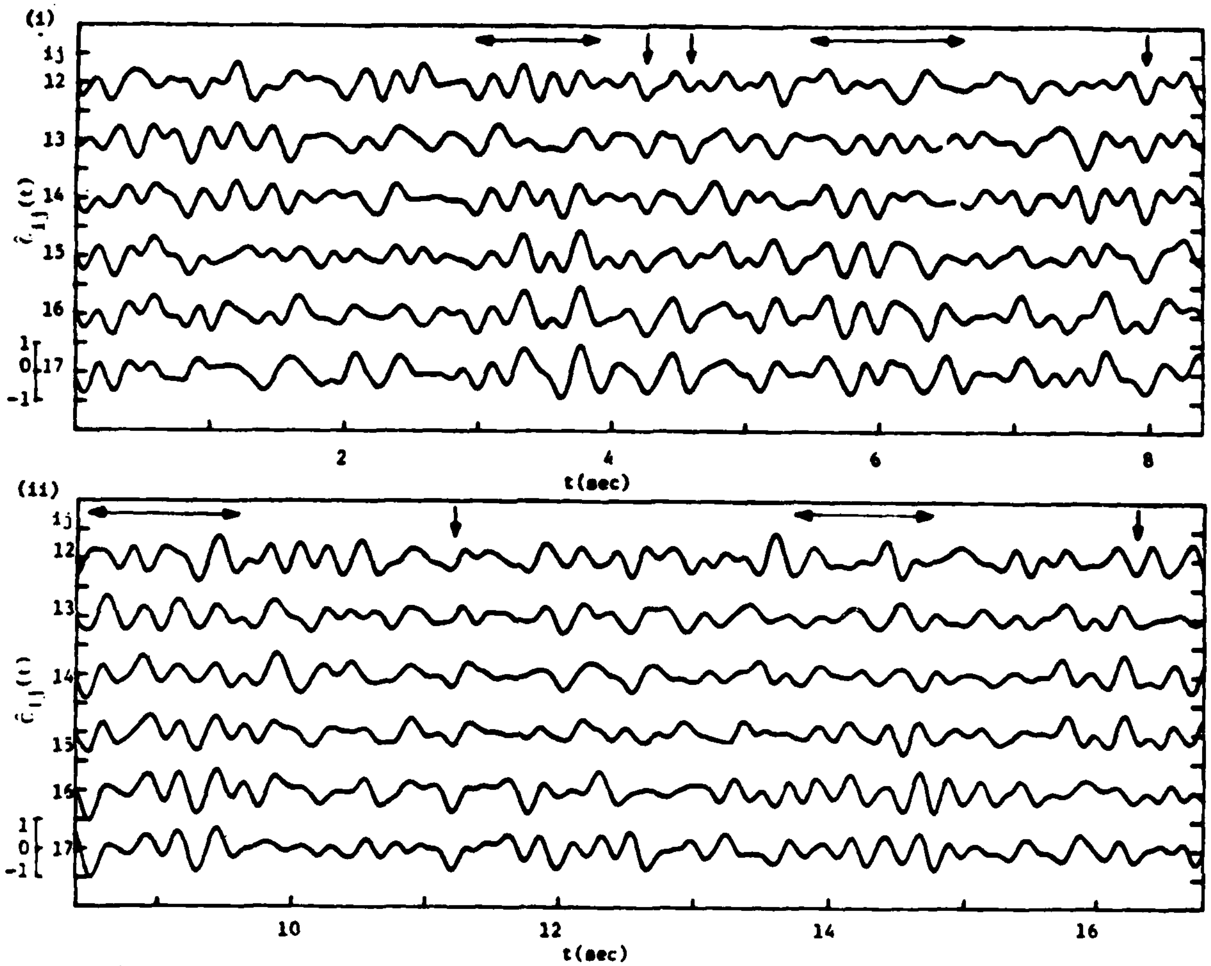
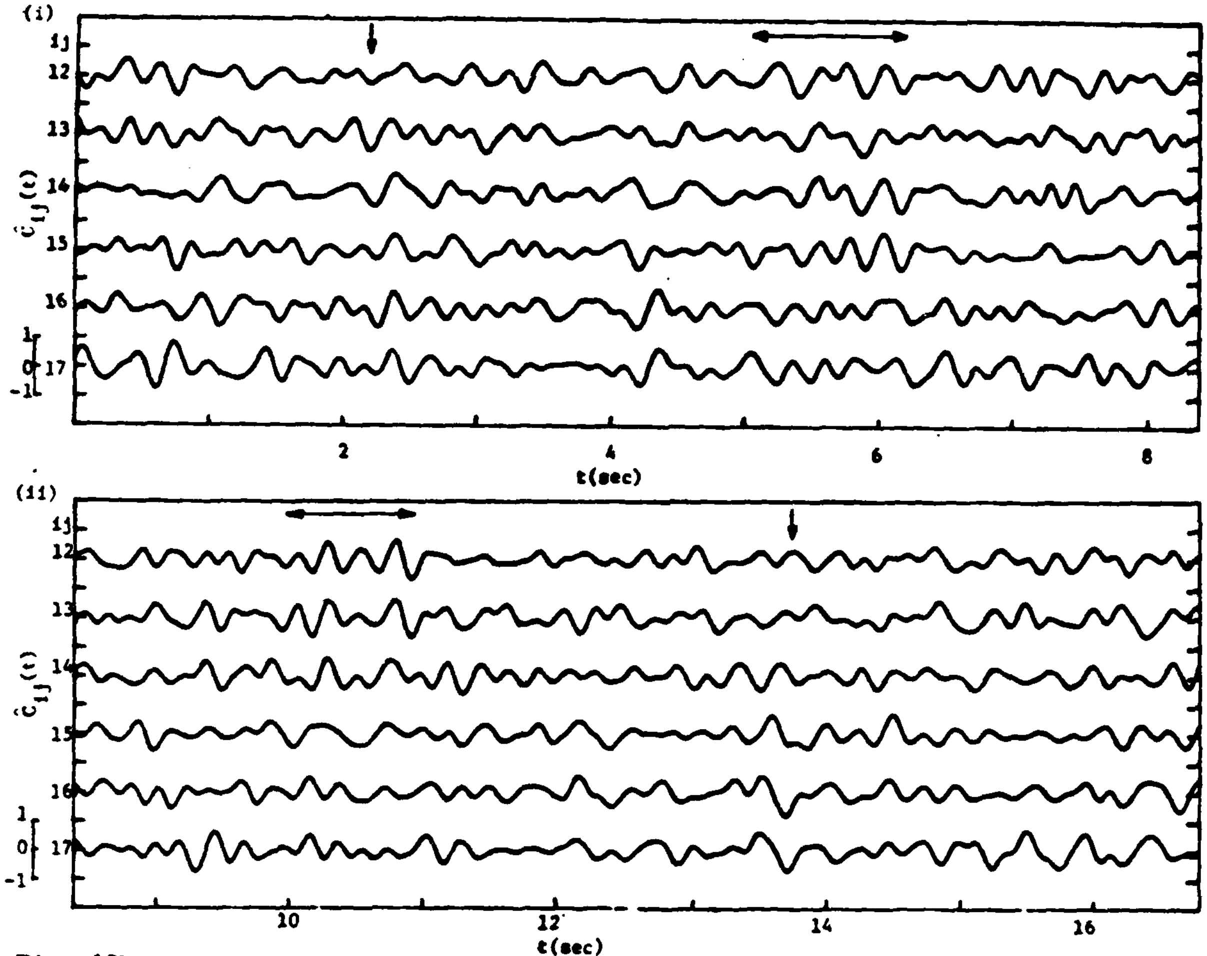


Fig 9.



(i)
ij
12
13
14
15
16
17
1
0
-1
$\hat{c}_{ij}(t)$
2
4
6
8
t(sec)
(ii)
ij
12
13
14
15
16
17
1
0
-1
$\hat{c}_{ij}(t)$
10
12
14
16
t(sec)

Fig 10a.


(i)
ij
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t(sec)
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-1
10
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16
t(sec)

Fig 10b.

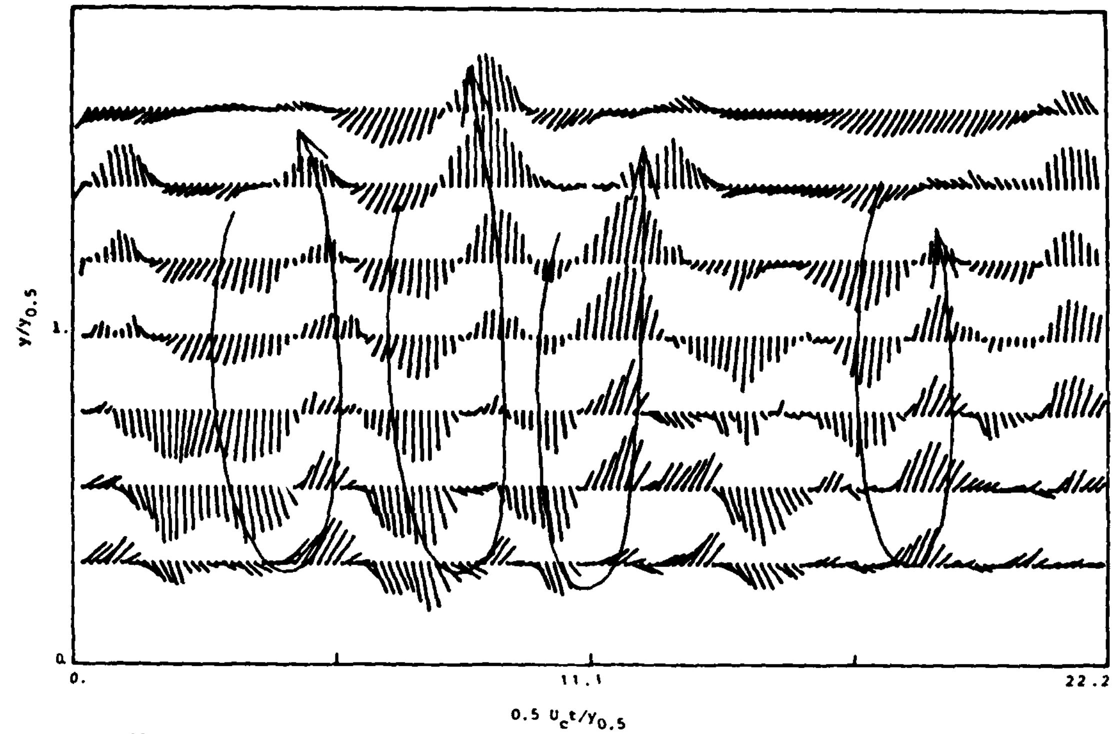

Fig 11a.

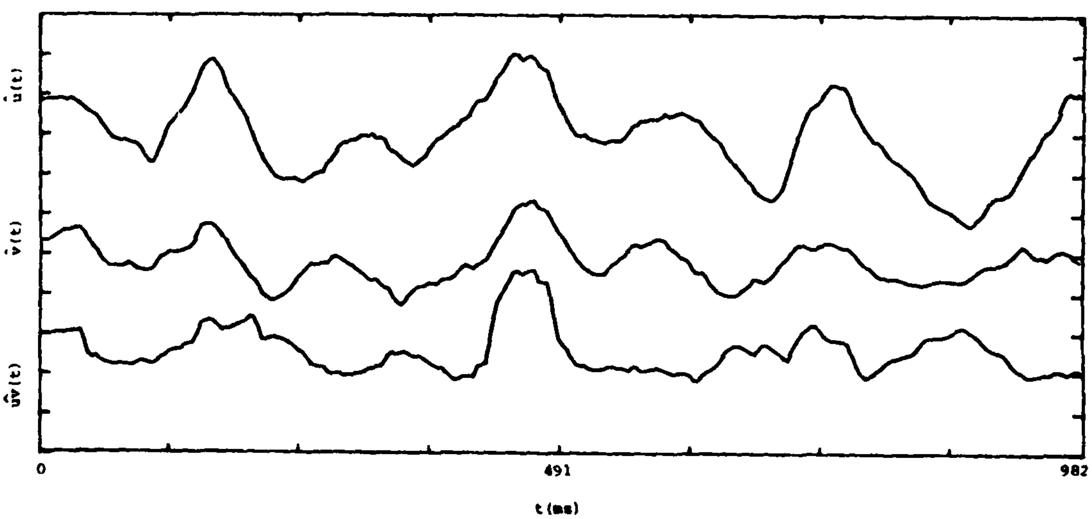

Fig 11b.


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